The NOAA-NASA CZCS Reanalysis Effort

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Satellite observations of global ocean chlorophyll span > 2 decades. However, incompatibilities between processing algorithms prevent us from quantifying natural variability. We applied a comprehensive reanalysis to the Coastal Zone Color Scanner (CZCS) archive, called the NOAA-NASA CZCS Reanalysis (NCR) Effort. NCR consisted of 1) algorithm improvement (AI), where CZCS processing algorithms were improved using modernized atmospheric correction and bio-optical algorithms, and 2) blending, where in situ data were incorporated into the CZCS AI to minimize residual errors. Global spatial and seasonal patterns of NCR chlorophyll indicated remarkable correspondence with modern sensors, suggesting compatibility. The NCR permits quantitative analyses of interannual and interdecadal trends in global ocean chlorophyll.
Key words: ocean color, satellites, coastal zone color scanner, remote sensing

Introduction

NASA and the international scientific communities have established a record of nearly continuous, high quality global ocean color observations from space since 1996. The Ocean Color and Temperature Scanner (OCTS: Nov. 1996-Jun. 1997), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS: Sep. 1997-present), and the Moderate Resolution Imaging Spectroradiometer (MODIS: Sep. 2000-present) have provided an unprecedented view of chlorophyll dynamics on global scales using modern, sophisticated data processing methods. A predecessor sensor, the Coastal Zone Color Scanner (CZCS: Nov. 1978-Jun. 1986), utilized processing methodologies and algorithms that are outdated by modern standards. Thus, the CZCS archive is severely limited for scientific analyses of interannual and interdecadal variability. This is an issue of fundamental importance to the study of global change.

In response, NOAA and NASA established an effort to reanalyze the CZCS record by utilizing advances in algorithms that are shared by modern remote sensing missions. In this paper we describe the methods and results of this effort, called the NOAA-NASA CZCS Reanalysis (NCR). Our methods involve the application of 1) recent algorithms to CZCS data to enhance quality and provide consistency with the modern sensors OCTS, SeaWiFS, and MODIS and 2) blending techniques[1] using satellite data and the extensive in situ archives maintained by the National Oceanographic Data Center (NODC)/Ocean Climate Laboratory (OCL) to minimize bias and residual error.

Our objective is to provide a high quality blended satellite-in situ data set that will enable a consistent view of global surface ocean chlorophyll and primary production patterns in two observational time segments (1978-1986 and 1996-present) spanning 2 decades. By reconstructing the historical CZCS data set, new insights can be gained into the processes and interactions involved in producing the interannual and interdecadal chlorophyll signal.

Background

CZCS and the Modern Ocean Color Sensors

The CZCS was a demonstration mission with two objectives: 1) to establish the technological and scientific feasibility of mapping ocean phytoplankton pigment concentrations from satellites and 2) determine the improvements that must be made for successful follow-on ocean color missions. The CZCS amply demonstrated the first objective. It also clearly indicated deficiencies in its design and operations that required correction to meet the scientific objectives of a successor mission. In approximate order of priority, these deficiencies, or required improvements were

1) the need for routine, continuous global synoptic observations,
2) better methods for characterizing aerosols,
3) the need for a dedicated calibration and validation program over the lifetime of the mission,
4) methods to account for multiple scattering by aerosols and the interaction between scattering by molecules and aerosols,
5) better signal-to noise ratios (SNR),
6) the need to produce estimates of chlorophyll, not pigment,
7) new information about chromophoric dissolved organic matter (CDOM),
8) the need to account for whitecap/foam reflectance,
9) improved pixel navigation.

All of the modern global missions meet the scientific requirements for ocean color observations. They are dedicated, routine observational platforms. They contain spectral bands in the near-infrared region of the spectrum to enable improved determination of aerosol characteristics. Dedicated, high quality in situ calibration/validation activities were established before launch. Complex algorithms were developed to account for aerosol multiple scattering and interactions with molecules. Signal-to-noise ratios were improved so that all the global missions have at least 500:1 for the visible wavelengths[2] instead of 200:1 for the CZCS[3]. All of the missions produce chlorophyll distributions as the primary geophysical product. A new spectral band was included at short wavelengths (near 410 nm) to help determine the distribution and abundance of CDOM. Whitecap/foam reflectance algorithms were developed and refined. Finally, precise navigation methods were developed pre-launch, including improved orbit determination, sensor attitude information, and geolocation algorithms.

CZCS Algorithm Deficiencies

Of course, some of the deficiencies of the CZCS data set, such as sensor design and operations activities, cannot be improved after the fact. However, recent advances in our understanding of atmospheric and oceanic optical principles that affect ocean color observations can be applied to the archive. The global CZCS data archive generally available from the NASA/Goddard Earth Sciences (GES)-Distributed Active Archive Center (DAAC) was produced in 1989 using algorithms that were standard for the time[4]. All of the subsequent algorithm improvements are utilized in the atmospheric correction and bio-optical algorithms for the modern sensors OCTS, SeaWiFS, and MODIS, and future sensors such as the Medium Resolution Imaging Spectrometer (MERIS), Global Imager (GLI), and the Visible Infrared Imaging Radiometer Suite (VIIRS).

The CZCS archive contains 8 major algorithm deficiencies when compared to modern sensors:

1) calibration,
2) navigation,
3) constant aerosol type,
4) single-scattering approximation for aerosols and no Rayleigh-aerosol interaction,
5) production of pigment rather than chlorophyll,
6) lack of whitecap/foam reflectance correction,
7) lack of correction to Rayleigh scattering due to non-standard atmospheric pressure,
8) lack of accounting for water-leaving radiance at 670 nm in high chlorophyll.

These deficiencies affect the representation of global chlorophyll and are a major reason for differences observed between the CZCS era and modern satellite observations of chlorophyll (shown later).

Blending of CZCS and In situ Data for Analysis of Seasonal Variability

Gregg and Conkright[1] combined the extensive archive of NOAA/National Oceanographic Data Center (NODC)/Ocean Climate Laboratory (OCL) chlorophyll data (>130,000 profiles) with the global CZCS archive at the GES-DAAC, using the blended analysis of Reynolds[5] to improve the quality and accuracy of global chlorophyll seasonal climatologies. The blended analysis produced a dramatically different representation of global, regional, and seasonal chlorophyll distributions than the archived CZCS[1]. Generally, the CZCS appeared to underestimate chlorophyll concentrations, globally by 8-35%. On regional and seasonal scales larger underestimates were common (20-40% and occasionally differences exceeded 100%).

While the blending approach appeared to have improved many of the deficiencies of the CZCS seasonal climatologies, vast areas of the ocean lacked in situ observations, limiting the ability of the method to correct for the deficiencies in the CZCS processing. Further improvements using the blended method require better CZCS data.

Methods

There are two main components to the NCR: 1) CZCS algorithm improvement (AI), and 2) blending with in situ data. The first component (AI) addresses the 8 major algorithm deficiencies in the global data set to produce a data set compatible with the modern processing methods used for OCTS, SeaWiFS, and MODIS. The second component (blending) improves the residual errors by utilizing the extensive coincident in situ data base maintained by NODC/OCL.

CZCS Algorithm Improvement

1) Calibration

A retrospective analysis of the CZCS record led to a revised calibration[6]. This revision is utilized by the reanalysis effort. Subsequent to publication of the revised calibration, a residual uncorrected temporal degradation trend in Band 4 (670 nm) was discovered[7]. This correction is applied in the CZCS AI to the time component of the calibration to begin at orbit 6750 instead of orbit 20000[8]. Also, masking for electronic overshoot is provided using methods described by Evans and Gordon[6].

2) Navigation

Poor orbit and attitude information from the Nimbus-7 spacecraft often produced degraded navigation of CZCS imagery. Typically, improvement has required intensive supervised methods to adjust imagery to match coastlines. Coastlines are not always available in the imagery. As a consequence, the global CZCS data set provided by the GES-DAAC only provides navigation derived from the onboard spacecraft attitude information and orbit ephemeris without additional correction.

We undertook an assessment of the CZCS navigation errors, to determine whether they were sufficiently stable to be corrected by bias-adjustment applied to the existing navigation. We adapted the method of island targets, originally developed for SeaWiFS[9], to the CZCS. In this method, the image data from multiple bands (usually two) are filtered to classify each pixel as land, water or clouds. Islands in the data are located as small groups of contiguous land pixels surrounded by water and uncontaminated by clouds. Island centroids are computed using the available navigation, and matched with reference island locations from a catalog based on the World Vector Shoreline database[9]. The island location errors are then used to estimate and characterize the navigation errors.

The method was adapted to use CZCS Bands 1 (443 nm) and 5 (750 nm), to avoid the saturation over land commonly occurring in the middle CZCS wavelengths (520, 550, and 670 nm). A Rayleigh scattering correction was applied to Band 1, and both bands were normalized to the solar zenith angle. We processed data from two periods from the mission (February 1980 and April 1982) to perform the initial analysis of the navigation errors. The results from both periods were fairly consistent, and showed errors that were negative in latitude and positive in longitude. The results from April 1982 (Fig. 1) show a cluster of points, centered on a latitudinal error of about –4 km and about 6 km in the longitudinal direction. The width of the cluster is about +/- 2 km in each direction. There are a number of scattered points, mostly resulting from island mismatches or misclassified pixels.

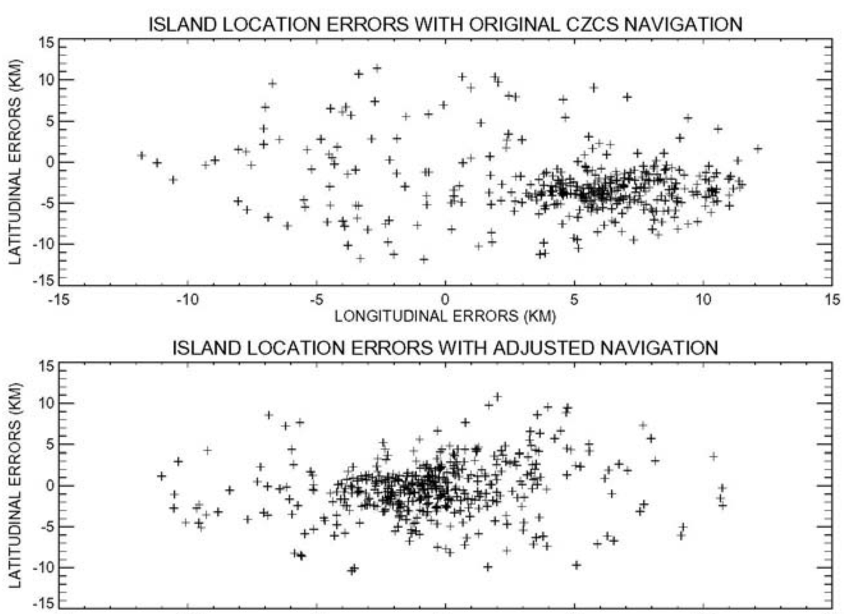

Figure 1. Navigational offsets in latitude and longitude in the original DAAC CZCS archive (top), and the effects of application of a bias adjustment used in the CZCS AI (bottom).

We characterized these errors in terms of along-scan, along-track (orbit position), and yaw (rotation about nadir) offsets. We estimated the following corrections to navigation: 5.5 pixels along-scan, 0.046 degree (5.9 km) along-track and 0.18 degree yaw. We applied these corrections to the CZCS latitudes and longitudes, and reprocessed the data from the same periods. The results (Fig. 1) show that the typical navigation errors are now close to zero, as seen in the cluster points. The distribution of points in the cluster is essentially the same, and indicates some residual variation in the navigation errors. We have processed other periods with these corrections, and achieved similar results.

3) Constant aerosol type, representing essentially a marine aerosol

Pre-specification of a constant aerosol type is one of the major deficiencies in the CZCS global data set[10,11]. However, it was a necessary deficiency because variable aerosol types could only be derived using intensive supervised methods[12]. We have developed an unsupervised method to derive aerosol characteristics using standard meteorological techniques. In our method, aerosol characteristics [defined by the aerosol reflectance ratio at 550 and 670 nm, or $\varepsilon(550,670)$] are determined at every location in a CZCS image where clear water conditions[12] are valid. Then the Successive Correction Method[13] (SCM) is used to extrapolate and interpolate $\varepsilon(550,670)$ values where the clear water method is invalid. Clear water $\varepsilon(550,670)$ values were obtained at Local Area Coverage (LAC) resolution (approximately 1 km) for each CZCS "scene" (an observational sampling period, typically about 2 minutes of orbit time) for the mission life. LAC processing was utilized to maximize the opportunities for obtaining clear water pixels. The $\varepsilon(550,670)$ data were then assembled into daily representations, binned onto an 1800 x 900 equal angle global grid, and the SCM was applied for each day. This produced daily global maps of $\varepsilon(550,670)$ values for the duration of the CZCS record with a resolution of about 20 km.

4) Single-scattering approximations for aerosols and no Rayleigh-aerosol interaction

Another serious deficiency in the global CZCS data set was the lack of a method for deriving multiple scattering aerosol reflectances and Rayleigh-aerosol interaction[14,15]. In the CZCS AI, we address this deficiency by utilizing the $\varepsilon(550,670)$ global maps described earlier, and modified the SeaWiFS aerosol scattering tables[16] to receive aerosol reflectance at 555 and 670 nm [$\rho_a(555)$ and $\rho_a(670)$]. First, $\rho_a(670)$ is derived from the imagery

$$L_a(670) = L_t(670) - L_r(670) - L_f(670) - t(670)L_w(670) \quad (1)$$

$$\rho_a(670) = \pi L_a(670)/[\cos\theta_o \, F_o(670)] \quad (2)$$

where L_a is the aerosol radiance (mW cm^{-2} μm^{-1} sr^{-1}), L_t is the total radiance at the satellite, L_r is the multiple-scattered Rayleigh radiance, L_f is the radiance derived from foam reflectance (see below), t is the diffuse transmittance of the atmosphere from the surface to the satellite[12,17] as a function of the sensor zenith angle θ, L_w is the water-leaving radiance, θ_o is the solar zenith angle, and F_o is the extraterrestrial irradiance. In Eq. (1), $L_w(670)$ is derived from the normalized water-leaving radiance $[L_w(670)]_N$

$$L_w(670) = [L_w(670)]_N \cos\theta_o t_o(670) \quad (3)$$

where t_o is the diffuse transmittance of the atmosphere from the sun to the surface and is defined similarly to t(670) except that θ_o is substituted for θ[17]. $[L_w(670)]_N$ is known at very low chlorophyll concentrations from the clear water principle[12] and is derived at higher concentrations from Siegel et al.[18] (see below). $\rho_a(550)$ is then obtained from the $\varepsilon(550,670)$ maps and adjusted to $\rho_a(555)$ by linear interpolation using the aerosol models in the SeaWiFS tables. Application of the modified SeaWiFS aerosol multiple scattering tables by input of $\rho_a(555)$ and $\rho_a(670)$ then provides us a complete spectral distribution of aerosol reflectance at the SeaWiFS bands, incorporating the effects of multiple scattering and Rayleigh-aerosol interactions, which are then merely interpolated to the CZCS wavelengths, similar to methods used for OCTS[17].

5) Production of pigment rather than chlorophyll

Previous CZCS processing yielded estimates of total pigment concentration (chlorophyll plus degradation products such as phaeopigments) as an index of the biomass of phytoplankton in surface waters. SeaWiFS and other modern ocean color missions generate estimates of chlorophyll, as it is a better index of the living component of phytoplankton and is therefore more useful for subsequent carbon uptake and primary production analyses. In our CZCS reanalysis we estimated chlorophyll concentration by using the Ocean Chlorophyll three-band CZCS bio-optical algorithm (OC3C). OC3C was empirically derived from the same extensive global *in situ* radiance-chlorophyll data set used to derive the operational SeaWiFS Ocean Chlorophyll four-band algorithm (OC4)[19]. The equation for OC3C is

$$\log C = 0.362 - 4.066R + 5.125R^2 - 2.645R^3 - 0.597R^4 \tag{4}$$

where C is the derived chlorophyll concentration (mg m^{-3}), and R is the maximum reflectance ratio between R_1 and R_2

$$R_1 = \frac{[L_w]_N(443)/F_o(443)}{[L_w]_N(550)/F_o(550)} \tag{5}$$

$$R_2 = \frac{[L_w]_N(520)/F_o(520)}{[L_w]_N(550)/F_o(550)} \tag{6}$$

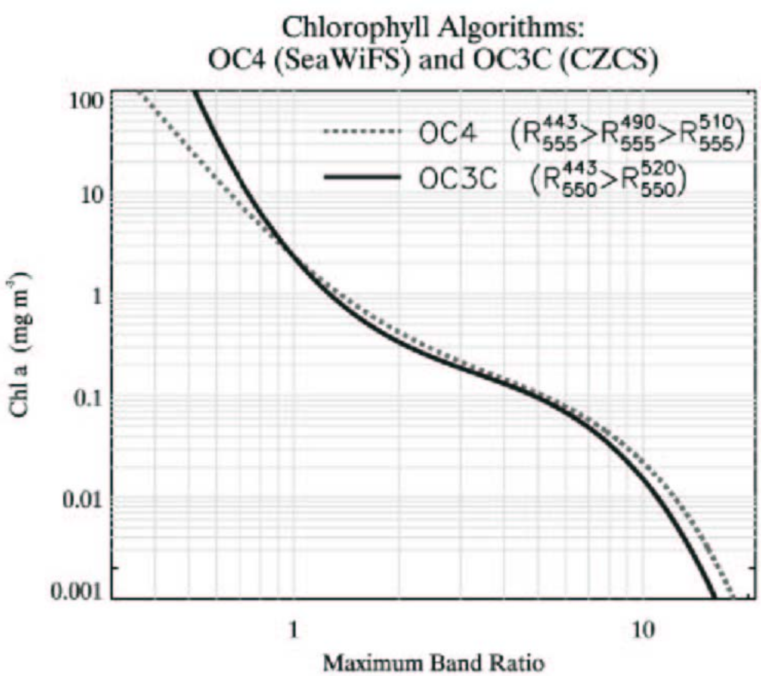

Figure 2. Comparison of the SeaWiFS OC4 Maximum Band Ratio algorithm used in the Version 3 processing and its OC3C analog used in the CZCS AI. The major differences occur at high chlorophyll concentrations, but all values > 25 mg m^{-3} were discarded in the AI, minimizing these differences.

where $[L_w]_N(\lambda)$ represents the normalized water-leaving radiance and $F_o(\lambda)$ is the extraterrestrial irradiance corrected for Earth-sun distance.

The equation for the SeaWiFS operational algorithm OC4[19] is

$$\log C = 0.366 - 3.067R + 1.930R^2 + 0.649R^3 - 1.532R^4 \tag{7}$$

where R is now the maximum of R_1, R_2, and R_3, which represent the SeaWiFS band ratios 443/555nm, 490/555nm, and 510/555nm, respectively. Both OC3C and OC4 are maximum band-ratio algorithms (MBR) that take advantage of the shift of the maximum of R toward higher wavelengths as chlorophyll concentration increases[20]. Thus, MBR chlorophyll algorithms have the potential to maintain the highest possible SNR over the very wide range of chlorophyll concentrations present in the global ocean. The high functional similarity between OC3C and OC4 (Fig. 2) and the fact that both were derived from a common data set ensures the comparability between CZCS and SeaWiFS chlorophyll estimates.

6) Lack of whitecap/foam reflectance correction

Wind-induced foam reflectance can impact the recovery of water-leaving radiances from ocean color sensors. All modern sensors provide a correction for foam reflectance, based on wind speed approximations. Accounting for whitecaps is now possible for the CZCS era with NOAA/National Center for Environmental Prediction (NCEP) reanalysis products (Table 1). We mimic the methods for SeaWiFS[21].

$$F = 6.497 \times 10^{-7} W^{3.52} \tag{8}$$

where W is the wind speed (m s^{-1}) and F is the foam reflectance (dimensionless). As with SeaWiFS, W is not allowed to exceed 8 m s^{-1} to reduce the overestimates of foam reflectance at high wind speeds[21].

It has also recently been demonstrated that foam exhibits spectral dependence[22,23]. This effect has been incorporated into the operational SeaWiFS processing[21] (Version 3) and is included in our CZCS reanalysis similarly

$$\alpha(\lambda) = 0.92 + 0.93\lambda - 2.15\lambda^2 + 0.78\lambda^3 \tag{9}$$

where λ is wavelength in μm, and $\alpha(\lambda)$ is a factor to account for the spectral dependence. Combining these effects we may derive the foam radiance $L_f(\lambda)$ used in our CZCS reanalysis

$$L_f(\lambda) = 0.4F\ \alpha(\lambda)\ t_d(\theta_o, \theta, \lambda)\ \cos\theta_o\ F_o(\lambda)\ D \tag{10}$$

where D is the Earth-sun distance correction, θ_o is the solar zenith angle, and t_d is the diffuse transmittance of the atmosphere, including both sun-to-surface and surface-to-sun components

$$t_d(\theta_o, \theta, \lambda) = \exp\{-[0.5\tau_r(\lambda)+\tau_{oz}(\lambda)][1/\cos\theta_o + 1/\cos\theta]\} \tag{11}$$

and τ_r and τ_{oz} are the Rayleigh and ozone optical thicknesses for CZCS bands[6]. The factor 0.4 is an empirical adjustment to F applied in the SeaWiFS processing[21].

7) Lack of correction to Rayleigh scattering due to non-standard atmospheric pressure

Rayleigh scattering can be affected by the amount of molecular constituents in the atmosphere, which can be parameterized in terms of atmospheric sea level pressure. This correction is routinely applied to the SeaWiFS operational products. Although the CZCS is minimally affected by the sea level pressure[24,25] because of low SNR, we include it here for consistency and because retrospective pressure data are now available from NOAA/NCEP (Table 1). We use CZCS multiple scattering Rayleigh tables[25].

Table 1. Input data sets required for atmospheric correction of CZCS data for compatibility with modern ocean color sensors. TOMS is the Total Ozone Mapping Spectrometer and CDC is the Climate Diagnostics Center, where the NCEP reanalyses are held and distributed.

Ancillary Atmospheric Variables		
Variable	**Purpose**	**Source**
Wind speed	Surface foam reflectance	CDC
Surface pressure	Rayleigh Scattering	CDC
Ozone	Gaseous absorption	TOMS

8) Lack of accounting for water-leaving radiance at 670 nm in high chlorophyll.

After two years of SeaWiFS operations, it was discovered that where large chlorophyll concentrations existed, substantial radiance in the near-infrared (NIR) bands (765 nm and 865 nm) left the water, violating the assumption of zero water-leaving radiance. Siegel et al.[18] provided an iterative correction method to estimate the water-leaving radiance at these bands and also at 670 nm for those who desired alternate atmospheric correction methods. The 670 nm method is directly applicable to the CZCS and is applied in our reanalysis. Unlike SeaWiFS, however, the so-called NIR-correction does not change the characterization of the aerosols in our CZCS reanalysis, just the amount. Aerosol characterization is derived independently from clear waters areas and is not affected by water-leaving radiance at 670 nm.

An overview of the algorithm improvement components is shown in Table 2, along with the algorithms used in the operational SeaWiFS processing, to illustrate the similarity. There remain two exceptions to the processing: 1) SeaWiFS corrects for ocean surface roughness effects due to sea surface wind, and 2) SeaWiFS provides a correction to sun glint outside a masking area where the glint is heaviest. The surface roughness effects are only important at very large solar zenith angles[26,27] (> 65°), and in our analysis only CZCS data with angles less than this limit are retained. Second, independent analyses of SeaWiFS data without applying the sun glint correction method have indicated no effect at the space and time scales used here.

Table 2. Comparison of methodologies used in the NOAA-NASA CZCS reanalysis (NCR) and the methods used in the SeaWiFS operational processing, Version 3.

CZCS AI/SeaWiFS Algorithm Compatibility

	CZCS AI	SeaWiFS
Calibration	Evans & Gordon 1994 retrospective reanalysis	SeaWiFS Project retrospective reanalysis
Navigation	Island target method Patt et al. (1997)	Island target method Patt et al. (1997)
Rayleigh Scattering	Exact multiple scattering Gordon et al. (1988) pressure-corrected	Exact multiple scattering Gordon et al. (1988) pressure-corrected
L_w(NIR)	Corrected at 670 nm Siegel et al. (2000)	Corrected at 765, 865 nm Siegel et al. (2000)
Aerosol Type	Characterized in clear water using 550 and 670 nm Objectively analyzed in high chlorophyll	Characterized using NIR bands 765 and 865 nm
Aerosol Scattering	SeaWiFS Multiple scattering/ Rayleigh-aerosol Tables Gordon and Wang (1994) modified to use 555 and 670 nm	SeaWiFS Multiple scattering/ Rayleigh-aerosol Tables Gordon and Wang (1994)
Foam Correction	Wind-dependent spectral correction Wang 2000; Frouin et al. 1996	Wind-dependent spectral correction Wang 2000; Frouin et al. (1996)
Bio-optical Algorithm	Maximum band ratio OC3C O'Reilly et al. (2000)	Maximum band ratio OC4 O'Reilly et al. (2000)

Blending Satellite and In situ Data

After improvement of CZCS data, it can be blended with in situ data from the NODC/OCL chlorophyll archive. The blended analysis involves two components: 1) in situ data insertion, and 2) modification of satellite data field to conform to the in situ data values while retaining its spatial variability. A correction for interannual variability[1] (IAV) is included in the NCR. The blended analysis uses CZCS AI data that are re-mapped to 1 degree equal angle resolution and is applied seasonally.

Previously Gregg and Conkright[1] defined four chlorophyll biomass domains to prevent unrealistic cross-regional influences resulting from blending. In the CZCS AI, these domain definitions have changed. They are now 0.35 mg m^{-3} to distinguish low chlorophyll domains from high, 0.15 mg m^{-3} for equatorial upwelling, and 0.4 mg m^{-3} for the Amazon River outflow.

Given that the CZCS data set has undergone modernization with respect to algorithm improvements as described above, we approach the blending of in situ data slightly differently than with the DAAC global data set. We assume that CZCS data are most accurate where chlorophyll concentrations are low and least accurate at high concentrations. This assumption is driven by the fact that at low chlorophyll concentrations the radiance received at the satellite is high, producing high signal and avoiding digitization error. This is especially true for the CZCS, which had much smaller SNR than modern sensors. Conversely, we assume that in situ data are most accurate at high chlorophyll. With these assumptions, we excluded all in situ values < 0.05 mg m^{-3} from the blended analysis.

The NCR utilizes the latest contributions to the NODC/OCL chlorophyll archive that were not present in the previous blending effort[1]. We also applied more rigorous quality control procedures for the blending. Specifically, data from the Surveillance Trans-Oceanique du Pacifique (SURTROPAC) program were removed because of reduced quality[28,29]. Also, other outliers in the North Central Pacific gyre were eliminated, along with tropical Atlantic data in 1979.

NCR Data Processing Overview

The processing for NCR occurs in 4 major steps. 1) Daily maps of ε(550,670) values are created using LAC processing to maximize clear water opportunities, and the SCM method to obtain valid ε(550,670) values where no clear water values exist. The ε(550,670) maps are produced on a 1800 x 900 equal angle grid (approximately 20 km resolution). 2) CZCS AI chlorophyll is derived using these daily ε(550,670) maps at Global Area Coverage (GAC) resolution (every fourth pixel and scan line) for each scene of the mission lifetime (approximately 66,000 scenes). 3) CZCS AI GAC resolution chlorophyll data are binned onto a 360 x 180 equal angle grid (1 degree resolution), and into seasonal (3 month) temporal increments. This is performed for each season and year for the CZCS record (1979-1986). This coarse spatial and temporal resolution enhances the effect of the blended analysis to correct residual errors. 4) IAV corrections are derived and then the blended analysis is executed on seasonal climatologies. Additionally, seasonal/yearly data are computed (no IAV correction is necessary) for each season and year of the CZCS life.

We evaluate the results of the NCR by comparing with the 1989 CZCS data set available from the GES-DAAC (called the DAAC CZCS), where pigment has been converted to chlorophyll using O'Reilly et al.[20]. The NCR is also compared with a SeaWiFS seasonal climatology from launch (Sep. 1997) to Dec. 2000. These comparisons are used to indicate an overall qualitative performance, emphasizing the similarities and differences of global distributions of chlorophyll. Quantitative evaluations involve root-mean-square (RMS) comparisons of the CZCS AI with the blended analysis (NCR). Results are compared to the RMS derived

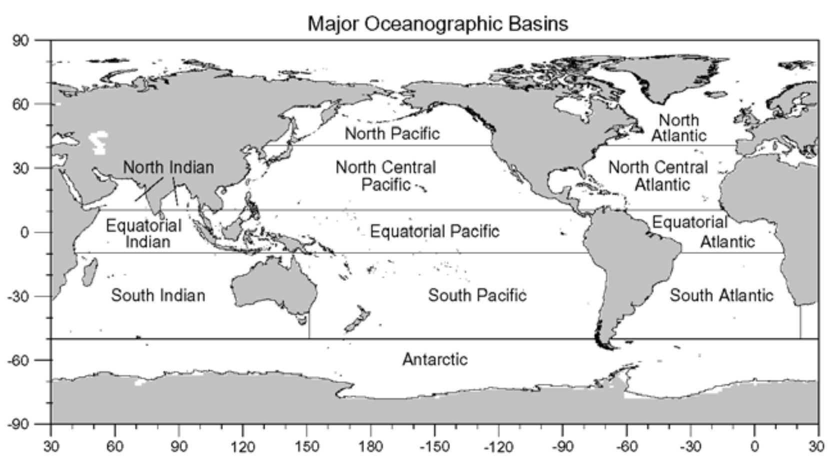

Figure 3. Geographic definition of the 12 major oceanographic basins of the global oceans.

from a blended analysis of the DAAC CZCS using the same in situ data set and the original DAAC CZCS. An additional quantitative analysis involves observation of global and regional mean differences between the NCR and the CZCS AI, as compared the differences between the DAAC CZCS and its blended analysis analog. Analyses are made globally and within each of the 12 major oceanographic basins of the global oceans (Fig. 3).

Results and Discussion

Comparisons Between CZCS AI/NCR and SeaWiFS

Comparison of the CZCS AI and NCR chlorophyll with SeaWiFS indicates a large degree of

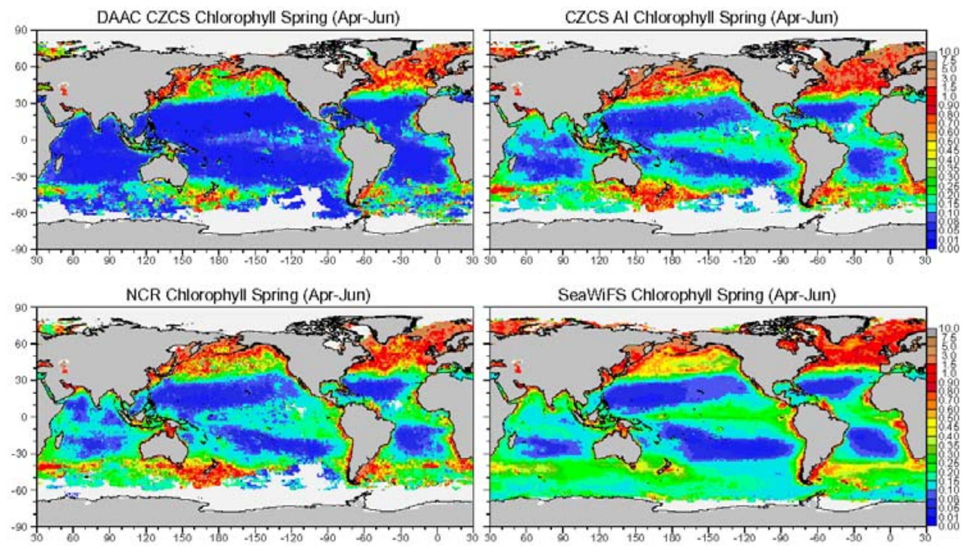

Figure 4. Global seasonal climatologies of the DAAC CZCS (top left), new reanalyzed CZCS without blending (top right), the blended-reanalyzed CZCS (NCR; bottom left), and SeaWiFS (bottom right) for spring defined for the Northern Hemisphere (April-June). Units are chlorophyll are mg m^{-3}.

consistency (Figs. 4-6). Seasons are defined according to the Northern Hemisphere convention: winter (Jan.-Mar.), spring (Apr.-Jun.), summer (Jul.-Sep.), and autumn (Oct.-Dec.). Sizes, shapes, and magnitudes of the mid-ocean gyres exhibit remarkable similarity. This is especially noticeable when compared to the DAAC CZCS pigment data converted to chlorophyll. The mid-ocean gyres are particularly noteworthy -- the DAAC CZCS gyres are vastly expanded relative to the CZCS reanalysis and SeaWiFS. These results suggest that the differences between the DAAC CZCS and SeaWiFS are mostly due to algorithm differences and not to natural variability. The CZCS AI exhibits correspondence especially in the broad gyres. It is this level of correspondence that strongly indicates consistency between these algorithms and the SeaWiFS algorithms.

There are substantial differences between the NCR seasonal climatologies and SeaWiFS, such as the northern high latitudes in autumn and near New Zealand in spring. But the overall correspondence suggests these differences may be due to natural variability, and not algorithms, which is the purpose of this effort.

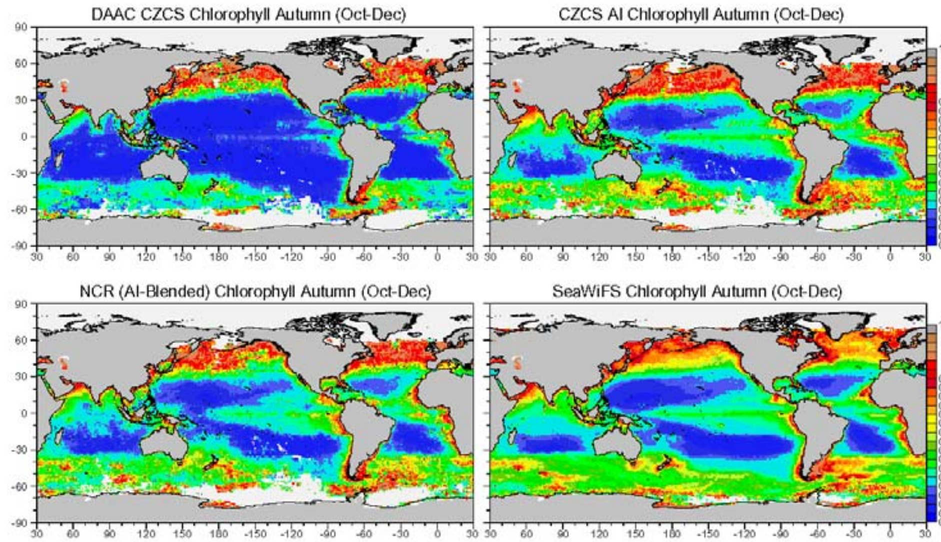

Figure 5. As in Fig. 4 for autumn (October-December).

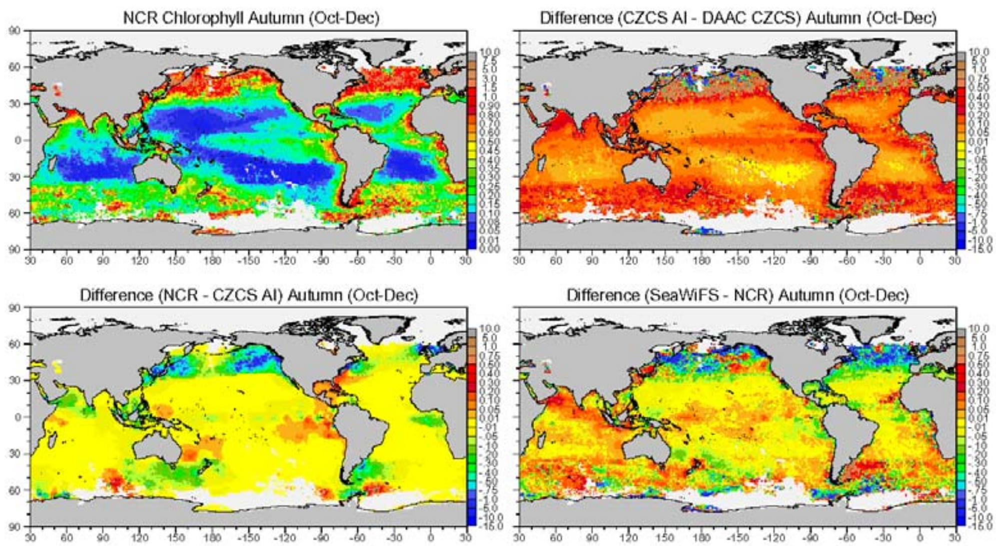

Figure 6. Difference fields between the chlorophyll data sets for autumn. Units are chlorophyll in mg m^{-3}. Top left: NCR chlorophyll. Top right: Difference CZCS AI – DAAC CZCS. Bottom left: Difference NCR – CZCS AI. Bottom right: Difference SeaWiFS-NCR. Units are chlorophyll mg m^{-3}.

A quantitative understanding of the effects of the NCR can be obtained by determining RMS difference between the CZCS blended and the unblended fields (the AI in the case of the reanalyzed CZCS, and the DAAC CZCS archive in the case of the previous version). This analysis provides an index of the departure of the blended fields from the original satellite fields, and indicates how closely the two fields agree. A small RMS difference indicates that the blended analysis made relatively minor adjustments to the original satellite field, and suggests agreement. A large RMS indicates that the original satellite field deviates greatly from the in situ data, and suggests poor quality of the original satellite field.

The RMS blended/unblended comparison indicates that the CZCS AI is a major improvement over the DAAC CZCS (Fig. 7). The previous DAAC CZCS blend represented a 70-81% change over the unblended DAAC CZCS data. This compares to 20-24% for the change of the NCR to the CZCS AI. This strongly suggests that blending the CZCS AI does not introduce large deviations, and that it is therefore a higher quality, more accurate representation of global ocean chlorophyll than the DAAC CZCS. The moderate adjustments produced by blending the CZCS AI with in situ chlorophyll yield an

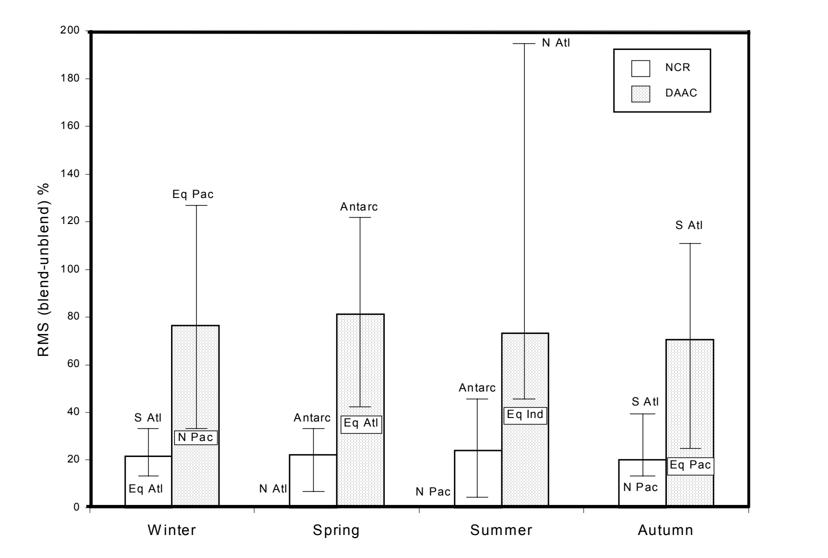

Figure 7. Global root-mean-square (RMS) differences between the reanalyzed CZCS Algorithm Improvement (AI) and the blended NCR, expressed as percent, compared to the DAAC CZCS blended analysis and the DAAC CZCS data set. Minima and maxima observed in any of the 12 major oceanographic basin (see Fig. 3) are indicated by the vertical lines. The basins corresponding to the minima and maxima are identified. Percent improvements for the NCR compared to the DAAC blend are 71.6%, 72.7%, 67.1%, and 71.3% for winter, spring, summer and autumn, respectively. The mean annual global improvement is 70.7%.

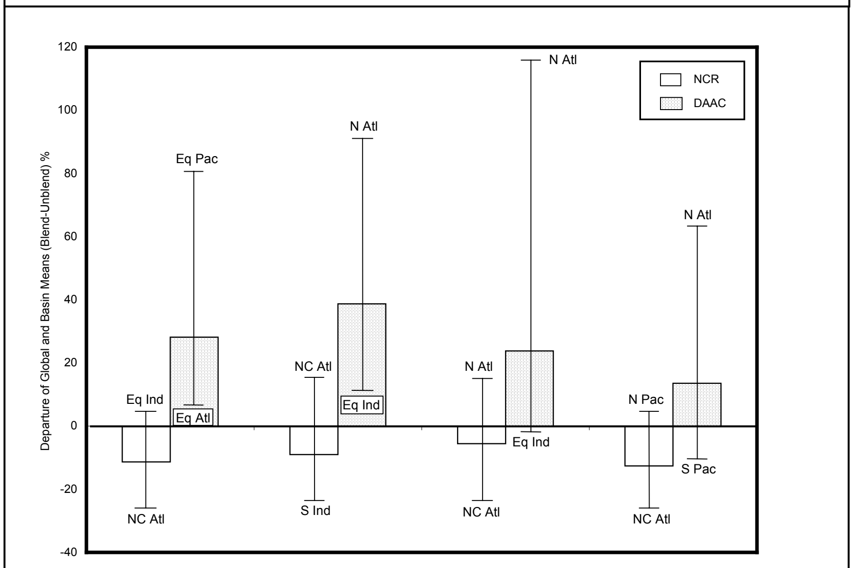

Figure 8. Departure of global mean (expressed as percent) for the NCR from the CZCS AI, and a comparison with the similar departure of the DAAC CZCS blended analysis from the DAAC CZCS data archive. The vertical lines indicate minimum and maximum departures observed in each of the 12 major oceanographic basins (Fig. 3). A negative (positive) value indicates that the blended analysis is lower (higher) than the CZCS data set. The global annual mean departure of the NCR is –9.6%, compared to the DAAC CZCS blend of 26.1%.

overall improved final product, which is the NCR.

Another characterization of the performance of the CZCS AI is the comparison of basin and global means by season before and after blending. Small changes indicate that the blended analysis is a modest residual error corrector. Large changes suggest that the original data set requires major bias correction to meet the chlorophyll fields represented by the in situ data. The NCR changed the global mean of the CZCS AI between –5.6 and –12.6% (the negative value indicates that the CZCS AI is an overerestimate) (Fig. 8). A similar analysis of the DAAC CZCS blend and its DAAC CZCS counterpart, using the same in situ data set, showed that the DAAC CZCS underestimates by 13.6% to 38.7% (Fig. 8). (These values are slightly different from Gregg and Conkright[1] due to application of a different in situ data set). Basin means also exhibit a narrower range of departures in the NCR than the DAAC CZCS blend. The global annual mean departure of the NCR is –9.6%, compared to the DAAC CZCS blend of 26.1%, again suggesting improvement.

The CZCS AI also appears to generate very reasonable estimates of normalized water-leaving radiance. According to Gordon et al.[12] and Evans and Gordon[6], the mode of the $[L_w(520)]_N$ and $[L_w(550)]_N$ wavelengths should be near 0.498 and 0.30 mW m^{-2} cm^{-1} sr^{-1}, respectively. These observations were based on in situ sampling. Analysis of the modes for the entire CZCS AI archive indicates excellent agreement, with a mean mode of 0.498 and 0.294, for $[L_w]_N(520)$ and $[L_w]_N(550)$, respectively (Fig. 9). There was no discernible temporal trend.

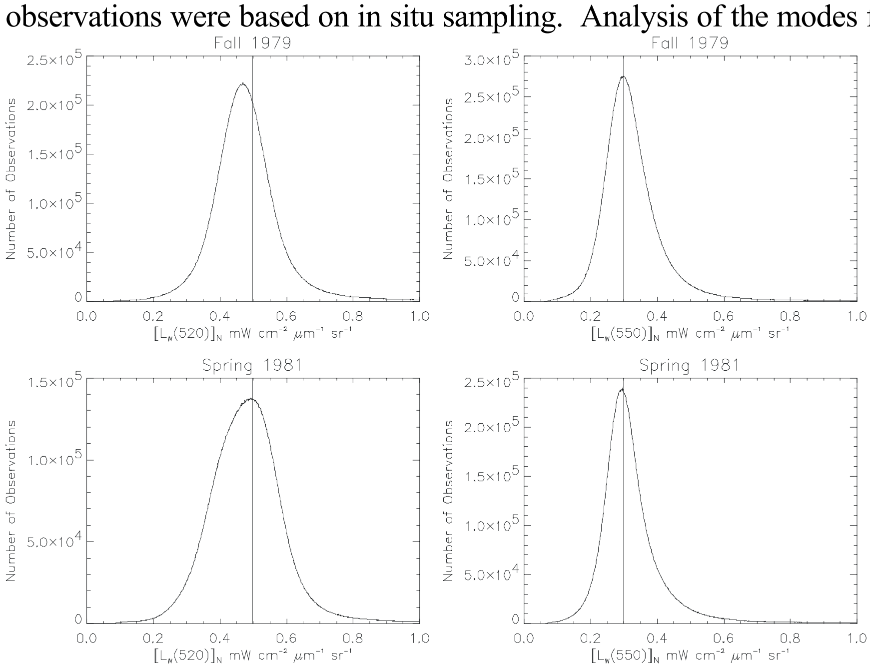

Figure 9. Representative histograms of normalized water-leaving radiances at 520 nm and 550 nm, $[L_w]_N(520)$ and $[L_w]_N(550)$, derived from all observations for the seasons and years indicated. The mean mode was 0.498 and 0.294 mW cm^{-2} µm^{-1} sr^{-1}, respectively for $[L_w]_N(520)$ and $[L_w]_N(550)$, which is very close to the expected 0.498, and 0.30 mW cm^{-2} µm^{-1} sr^{-1}. The solid vertical line indicates the location of the expected

Residual Problems with CZCS

We have applied improved algorithms to the CZCS archive to produce a global chlorophyll data set that is compatible with modern ocean color sensor data. However, there are still residual problems with the CZCS based on its design and operation that present obstacles to producing a seamless time series. These are primarily 1) poor sampling, 2) lack of bands in the NIR to enable improved identification of aerosol characteristics, and 3) poor SNR. Our methods here have done much to alleviate the problems with aerosol identification and SNR, but sampling remains a problem that is insurmountable through algorithm improvement or processing methodologies.

1.0 Poor Sampling by the CZCS.

As a demonstration mission, the CZCS was only operated sporadically, producing sampling alias. OCTS, SeaWiFS, MODIS and future global ocean color sensors are operational missions that routinely collect data globally. Some small sampling aliases may occur in these missions from inadequate solar irradiance occurring in local winter in the high latitudes. But the sparse sampling by the CZCS in local winter was so severe that, for example, there were very few observations in January in the North Atlantic above 40^o latitude. Consequently the winter seasonal mean was over-represented by February and especially March observations. This sampling bias affects the comparison with SeaWiFS seasonal means, which do not contain a similar bias. Therefore, CZCS observations in the North Pacific and North Atlantic basins north of 40^o in winter and autumn, and in the Antarctic south of 40^o in spring and summer, should be viewed with caution, despite the improvements in the NCR from upgrade of algorithms and blending. Comparisons with other mission data in these seasons are unrepresentative on large scales, even if utilizing co-located data only.

2.0 Lack of Bands in the NIR to Enable Unequivocal Identification of Aerosol Characteristics

All modern ocean color missions contain bands in the NIR, typically at 765 and 865 nm, to distinguish aerosol characteristics. Except at high chlorophyll concentrations[25], water is completely absorbing at these wavelengths and thus an unequivocal identification of scattering aerosols is possible. (Absorbing aerosols are difficult to identify using only information at these NIR bands). The CZCS had quantitative ocean-viewing bands only at 443, 520, 550, and 670 nm, all of which are affected by chlorophyll. However, at low chlorophyll concentrations, $[L_w(520)]_N$, $[L_w(550)]_N$, $[L_w(670)]_N$ are known[6,12]. Our method for deriving aerosol characteristics takes advantage of the knowledge in these so-called clear-water areas, and extrapolates to areas with high chlorophyll using standard methods developed for meteorology and applied to oceanographic problems[30], called the SCM or also known as objective analysis. The success of this methodology to reproduce the spatial variability of aerosols depends upon the number of observations over clear water. Occasionally individual CZCS scenes contained no valid ocean pixels other than high chlorophyll. For example, some scenes were mostly over land and contained only a small fraction of high chlorophyll coastal areas. For this reason, we aggregate ε(550,670) over a day, so that there is the possibility of a preceding or succeeding scene, or even a scene from a different orbit, that can provide a clear water ε(550,670) determination that is close enough to the high chlorophyll pixels to be valid. Of course, it is impossible for the SCM to detect aerosol fronts that are located entirely within high chlorophyll. But if there are just a few clear water pixels within the high chlorophyll regions and under the new aerosol type, the SCM can resolve the front. Considering that the dynamics of ocean chlorophyll domains and aerosols are vastly different, it would seem an unlikely possibility that some detection of aerosol fronts cannot be made, although it probably occurs

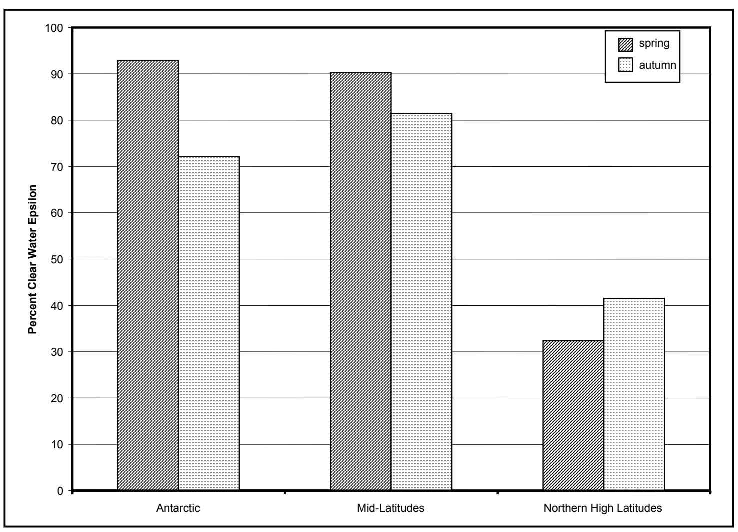

Figure 10. Percentage of pixels where ε(550,670) values (representing aerosol type) were derived from clear water observations, as opposed to those obtained from extrapolation with SCM. Observations were from the entire archive for spring and autumn.

occasionally.

To understand the sensitivity of the CZCS AI to the aerosol detection methodology, we pre-specified $\varepsilon(520,670)$ and $\varepsilon(550,670)$ to a fixed value of 1.0, representing a marine aerosol as in the DAAC CZCS. We applied our methodology otherwise identical to the CZCS AI, including multiple scattering aerosols. The global differences in spring and autumn were only 5.9% and 4.9%, respectively, compared to AI with variable ε. The differences were only 2.5% and 3.3%, respectively for spring and autumn, between the blended results. These results illustrate the correction ability of the blended analysis. The fixed ε experiment produced lower estimates of chlorophyll than the NCR, which is consistent with the algorithm behavior and with the observations of underestimates in the DAAC CZCS[1].

A further analysis involved identifying the percentage of pixels where clear water $\varepsilon(550,670)$ values were available (derived ε), as opposed to those underlying $\varepsilon(550,670)$ extrapolated from SCM. These results indicate often very high percentages of derived ε, especially in mid-latitudes (between –50 and 40 latitudes) (Fig. 10). Reduced percentages of derived ε are observed in the northern high latitudes, but even here, despite the massive spring bloom of high chlorophyll, there are still >30% of the chlorophyll pixels underlying derived ε values from low chlorophyll (clear water) regions. The Antarctic indicates generally good derived ε coverage.

3.0 Poor Signal-to-Noise Ratios (SNR)

The CZCS SNR's, at about 200:1, are much smaller than modern sensors, with 500:1 or better now common[3]. This limits the dynamic range of chlorophyll the CZCS is able to detect, but more importantly may affect the quality of the derived products. We minimize these effects by excluding all pixels where the water-leaving radiance diffusely transmitted to the satellite [$tL_w(\lambda)$, where λ = 443, 520 and 550] is less than 2 digital counts. This assures sufficient signal in the data to exceed the noise level. Additionally, the binning of $\varepsilon(550,670)$ to a 20-km grid involves averaging and thus reduces the sensitivity of the results to the low SNR.

Summary and Conclusions

The CZCS global ocean chlorophyll archive was revised using compatible atmospheric correction and bio-optical algorithms with modern generation ocean color sensors, such as OCTS, SeaWiFS, and MODIS. The revision involved two components, 1) algorithm improvement (AI), where CZCS processing algorithms were improved to take advantage of recent advances in atmospheric correction and bio-optical algorithms, and 2) blending, where in situ data were incorporated into the final product to provide improvement of residual errors. The combination of the two components is referred to as the NOAA-NASA CZCS Reanalysis (NCR) Effort. The results of the NCR indicate major improvement from the previously available CZCS archive maintained by the NASA/GES-DAAC. Blending with in situ data produced only a 22% adjustment to the CZCS AI field, compared to a 75% percent adjustment required for the DAAC CZCS. This represented a 71% improvement. Global annual means for the NCR suggested a small overestimate of 9.6% from the CZCS AI, compared to a mean 26% underestimate for the DAAC CZCS blend. Frequency distributions of normalized water-leaving radiances at 520 and 550 nm were in very close agreement with expected. Finally, observations of global spatial and seasonal patterns indicated remarkable correspondence with SeaWiFS, suggesting data set compatibility.

This revision can permit a quantitative comparison of the trends in global ocean chlorophyll from 1979-1986, when the CZCS sensor was active, to the present, beginning in 1996 with OCTS, SeaWiFS, and MODIS. The overall spatial and seasonal similarity of the data records of CZCS and SeaWiFS strongly suggests that differences are due to natural variability, although some residual effects due to CZCS sensor design or sampling may still exist. We believe that this reanalysis of the CZCS archives can enable identification of interannual and interdecadal change.

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